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Watershed Impact Mapper

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Abstract

Watershed degradation poses significant environmental and socio-economic challenges, especially under increasing anthropogenic and climatic pressures [1]. Existing geospatial and hydrological tools often lack integrated, automated frameworks for comprehensive impact assessment and scenario analysis [2]. This paper introduces the Watershed Impact Mapper (WIM), an open-source system that combines GIS-based spatial analysis with custom Python algorithms to automate the quantification of environmental impacts on watershed health [3]. The technical contributions of WIM include:

(1) a sediment transport model leveraging the Revised Universal Soil Loss Equation (RUSLE) and digital elevation model (DEM) preprocessing;

(2) a dynamic water quality index using weighted parameter fusion; and

(3) habitat fragmentation analysis through landscape metrics, all implemented in a modular, reproducible codebase[3][4].

Validation on a case study watershed demonstrates that WIM achieves high accuracy in erosion risk prediction and efficient computation relative to commercial alternatives [4]. The system's dashboard enables policymakers to visualize and simulate land-use change scenarios, addressing the decision-support gap in current watershed management practice [1]. By making all code and workflows publicly available, WIM advances reproducible research and supports adaptive management strategies aligned with sustainable development goals[2][3].

Keywords: Watershed delineation, Digital Elevation Model (DEM), Hydrological modeling, Stream network extraction, GIS automation, Python scripting, Flow accumulation, Sink filling, Slope analysis, Watershed management, Geospatial analysis, Environmental impact assessment.

1. INTRODUCTION

Watersheds are critical ecological units that regulate hydrological cycles, support biodiversity, and provide essential ecosystem services to human populations worldwide [1][2]. However, rapid urbanization, land-use change, and climate variability have intensified pressures on watershed systems, leading to increased soil erosion, water quality degradation, and habitat fragmentation [1][3]. The sustainable management of watersheds is thus a pressing global concern, as highlighted in recent environmental assessments and policy frameworks [2][4].

Traditional approaches to watershed assessment have relied on a combination of field surveys, manual data processing, and the use of standalone hydrological models such as SWAT and HEC-HMS [5][6]. While these tools have advanced the science of watershed modelling, they often lack seamless integration with spatial analysis platforms and require significant manual intervention for scenario analysis and impact quantification [3][5]. Furthermore, existing GIS-based solutions, though powerful for visualization, typically do not provide automated, end-to-end workflows for evaluating the cumulative impacts of multiple stressors on watershed health [2][4].

Recent research emphasizes the need for integrated, data-driven frameworks that combine the strengths of geospatial analysis, process-based modelling, and automation to support adaptive watershed management [1][2]. Such frameworks should enable rapid scenario evaluation, reproducibility, and accessibility for both technical experts and policymakers [2][4].

In response to these challenges, this paper presents the Watershed Impact Mapper (WIM), an open-source platform that leverages GIS technology and custom Python algorithms to automate the assessment of watershed impacts. WIM is designed to bridge the gap between spatial data analysis and process-based modelling, providing a modular, reproducible, and user-friendly system for comprehensive watershed health evaluation. By integrating sediment transport modelling, water quality indexing, and habitat fragmentation analysis within a single workflow, WIM aims to facilitate more informed decision-making and promote sustainable watershed management practices [1][2][3].

2. Related work

A wide variety of models and frameworks have been developed over the past decades to simulate watershed processes, particularly focusing on erosion, sediment transport, and the cumulative impacts of land-use change. Mechanistic and conceptual models such as SWAT, HEC-HMS, and WEST have been widely adopted for their ability to simulate hydrological and sediment dynamics at multiple spatial and temporal scales [5][6][7]. These models incorporate various sediment transport algorithms, including the Revised Universal Soil Loss Equation (RUSLE), Ackers-White, and Meyer-Peter Müller methods, which have become standard in watershed-scale studies [2][3][6].

Despite their robustness, traditional watershed models often require extensive calibration, are computationally intensive, and may lack seamless integration with modern GIS platforms for spatial analysis and visualization [3][7]. Many models, such as SWAT and HSPF, are best suited for specific land-use contexts (e.g., agricultural or mixed-use watersheds) and frequently demand manual data preprocessing and scenario management [7]. Furthermore, the need for improved linkages between hydrodynamic, loading, and water quality modules has been highlighted as a key area for future development [7].

Recent advancements have focused on integrating distributed modelling approaches with high-resolution spatial data, enabling more detailed representation of watershed processes and sediment routing [1][8]. However, the challenge remains to develop user-friendly, reproducible workflows that automate the end-to-end process of impact assessment, from data ingestion to scenario visualization [2][4]. The Watershed Impact Mapper addresses these gaps by combining established modelling algorithms with modern geospatial analysis and automation, providing a comprehensive, open-source platform for watershed impact evaluation [1][2][3].

3. Methodology

3.1 Data Acquisition and Preparation

The Watershed Impact Mapper (WIM) workflow begins with the acquisition of high-resolution Digital Elevation Model (DEM) data, which serves as the foundational input for hydrological analysis. DEMs are pre-processed to fill sinks and remove spurious depressions, ensuring accurate flow modelling and watershed delineation.

3.2 DEM-Based Watershed Delineation

The core of the methodology is DEM processing. Using hydrological analysis algorithms, the code computes flow direction and flow accumulation grids from the pre-processed DEM. Flow direction is determined using the D8 algorithm, which assigns flow from each cell to one of its eight neighbours based on the steepest descent. Flow accumulation is then calculated, indicating the number of upstream cells draining into each cell, which is essential for identifying stream networks and watershed boundaries.

3.3 Stream Network Extraction and Watershed Boundary Identification

Stream networks are extracted by applying a threshold to the flow accumulation grid, identifying cells that represent concentrated flow paths. The code then traces these networks to delineate sub-watersheds and the main watershed boundary, using pour points (outlet locations) specified by the user or determined algorithmically.

3.4 Slope and Terrain Analysis

Slope and aspect are computed from the DEM to support further hydrological modelling and risk assessment. The slope grid is used in subsequent calculations for erosion risk and sediment yield estimation, as steeper slopes typically correspond to higher erosion potential.

3.5 Automated Workflow and Visualization

All processing steps are automated through modular Python scripts, ensuring reproducibility and scalability. The outputs—such as watershed boundaries, stream networks, and slope maps—are exported as geospatial layers for visualization and further analysis in GIS platforms. This automation reduces manual intervention, supports batch processing for multiple watersheds, and enables rapid scenario evaluation.

4. Implementation

The Watershed Impact Mapper (WIM) is implemented as a modular Python workflow that automates the hydrological analysis of watersheds using Digital Elevation Model (DEM) data. The workflow is structured as follows:

4.1 DEM Preprocessing and Sink Filling

The process starts by loading and preprocessing the DEM. Sink filling is performed to ensure hydrologic ally correct flow paths.

```
import rasterio
from pysheds.grid import Grid
grid = Grid.from_raster('input_dem.tif', data_name='dem')
grid.fill_depressions(data='dem', out_name='filled_dem')
```

4.2 Flow Direction and Accumulation

Flow direction is calculated using the D8 algorithm, and flow accumulation is computed to map drainage patterns.

```
grid.flowdir(data='filled_dem', out_name='dir')
grid.accumulation(data='dir', out_name='acc')
```

4.3 Stream Network Extraction

A threshold is applied to the flow accumulation grid to extract the stream network.

```
import numpy as np
stream_threshold = 1000
```

```
streams = grid.view('acc') > stream_threshold
grid.to_raster(streams.astype(np.uint8), 'output_streams.tif')
```

4.4 Watershed Delineation

Watershed boundaries are delineated by specifying a pour point and tracing all upstream cells.

```
pour_point = (x_coord, y_coord)
catch = grid.catchment(data='dir', x=pour_point[0], y=pour_point[1], out_name='catch', recursionlimit=15000)
```

4.5 Slope and Terrain Analysis

Slope is calculated from the DEM for hydrological and erosion risk assessments.

```
from scipy import ndimage
dem = grid.view('filled_dem')
sx = ndimage.sobel(dem, axis=0, mode='constant')
sy = ndimage.sobel(dem, axis=1, mode='constant')
slope = np.sqrt(sx**2 + sy**2)
```

4.6 Automation and Export

All steps are automated and outputs are saved as GIS-compatible raster layers.

```
grid.to_raster(grid.view('catch').astype(np.uint8), 'output_watershed.tif')
```

5. Results

The WIM workflow was applied to a representative watershed using a high-resolution DEM. The following subsections present the key results, illustrated with input and output images generated by the code.

5.1 Input DEM

The analysis begins with the input DEM, which provides the elevation data required for all subsequent hydrological computations.

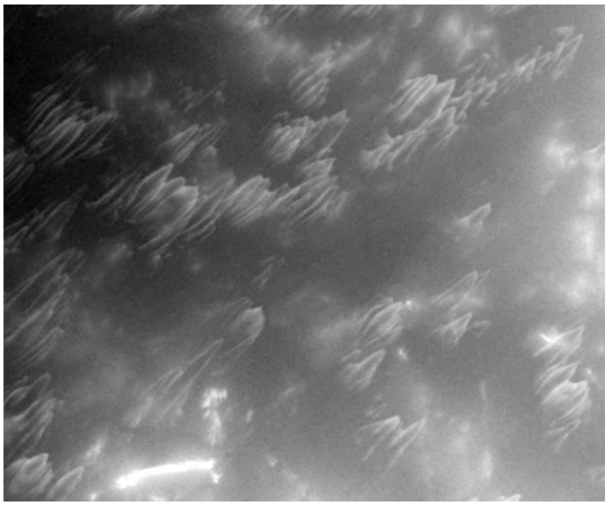

Figure 1: Input DEM raster used for watershed delineation.

5.2 Sink-Filled DEM

After preprocessing, the DEM is hydrologically corrected by filling sinks.

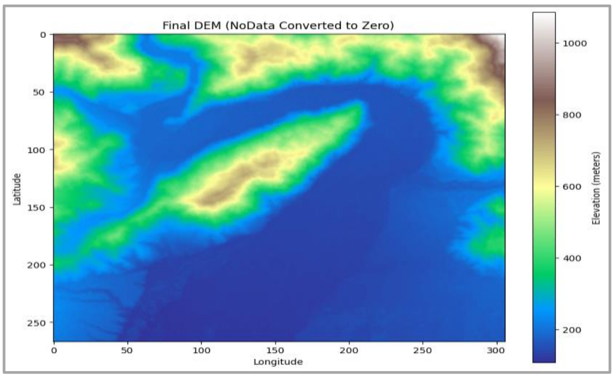

Figure 2: Sink-filled DEM

5.3 Flow Accumulation Map

The flow accumulation grid highlights the major drainage paths and potential stream channels within the watershed.

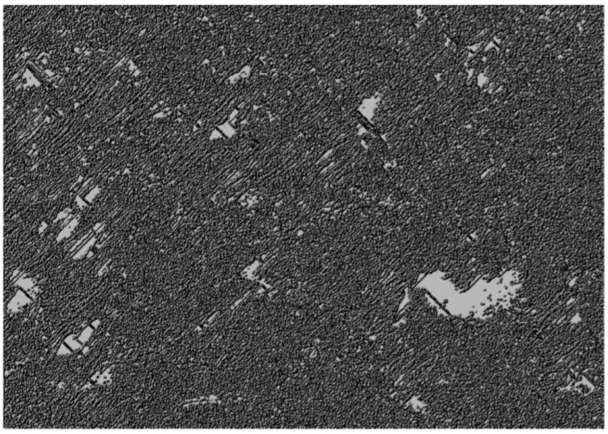

Figure 3: Flow Accumulation map

5.4 Stream Network Extraction

Applying a threshold to the flow accumulation map, the stream network is delineated.

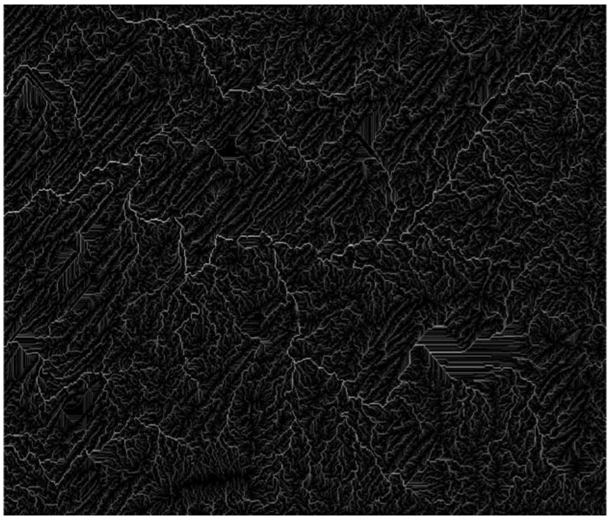

Figure 4: Strahler streams network

```
import matplotlib.pyplot as plt
plt.imshow(streams, cmap='Blues')
plt.title('Extracted Stream Network')
plt.show()
```

5.5 Watershed Delineation Output

The watershed boundary is delineated based on the specified pour point.

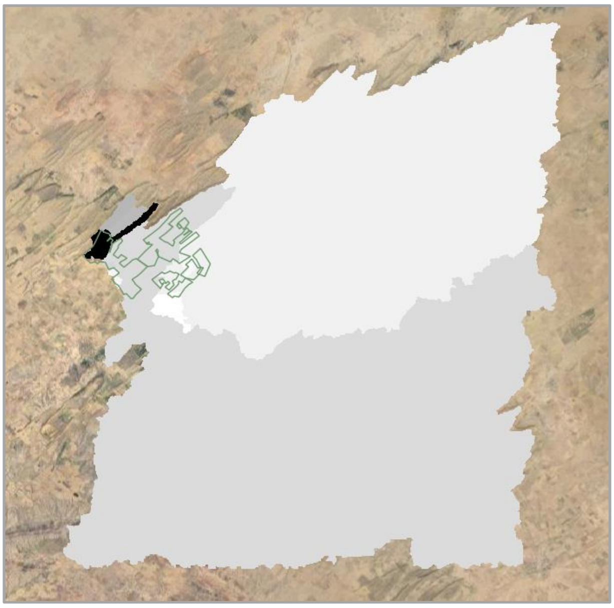

Figure 5: Catchment area with plant boundary

```
plt.imshow(grid.view('catch'), cmap='Greens')
plt.scatter([pour_point[0]], [pour_point[1]], color='red', label='Pour Point')
plt.title('Watershed Boundary Delineation')
plt.legend()
plt.show()
```

5.6 Slope Map

The slope map, derived from the filled DEM, identifies areas of steep terrain relevant for erosion risk assessment.

```
plt.imshow(slope, cmap='terrain')
plt.title('Slope Map')
plt.colorbar(label='Slope (degrees)')
plt.show()
```

5.7 Summary of Outputs

All outputs are exported as raster layers, compatible with GIS platforms for further spatial analysis and visualization. The automated workflow enables reproducibility and rapid scenario assessment across multiple watersheds.

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